SWERR-TR-72-35

INFRARED NONDESTRUCTIVE TESTING OF LAMINATED STRUCTURES AND ELECTRICAL CIRCUITS

TECHNICAL REPORT

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U. S. ARMY WEAPONS COMMAND

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Infrared nondestructive testing (IRNDT) techniques and instrumentation, developed under In-House Laboratory Independent Research funding in the Research Directorate of the Weapons Laboratory at Rock Island, were used successfully to detect unbonded areas in laminated structures. A high-speed infrared camera was used to monitor the thermal signature of the samples while they were being heated. Two methods of external sample heating were used in the IRNDT investigations, a 35 watt, continuous wave, CO_2 laser and a 250 watt infrared lamp. The results obtained with each heat source were compared to determine the relative merits of each, and results are presented. The infrared camera was also utilized to detect an incipient failure in the electrical circuit board of a digital voltmeter.

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2. CO_2 Laser						
3. Nondestructive Testing						
4. Infrared Camera						
5. Radiometer						
6. Thermal Image						
7. Flaw Detection						

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ABSTRACT

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CONTENTS

OBJECTIVE

The objective of this investigation was to develop new infrared nondestructive testing (IRNDT) techniques for the detection of surface and subsurface flaws in metallic and organic materials with a high-speed infrared camera.

INTRODUCTION

Infrared techniques have been used by many investigators for the nondestructive testing of various types of structures. For example, Kutzscher and Zimmerman used IRNDT techniques to evaluate bonds in airospace structures;[1] while Vogel used these techniques to evaluate bonds in armor plate, rubber coatings, and missile motor cases;[2] and Kubiak used IRNDT to detect fatigue cracks and other near-surface defects in aircraft and missile structures.[3] In each of the investigations mentioned, a regular heat lamp or a high intensity zenon lamp was used to heat the samples being tested while an infrared camera was used to detect ary thermal anomalies that developed. In addition, during FY70 and FY71, the Research Directorate of the Weapons Laboratory at Rock Island submitted reports on new active and passive IRNDT techniques that relied on the use of a CO_2 laser heat source and an infrared radiometer to detect thermal anomalies resulting from programmed flaws in metallic specimens.

In the Research Directorate investigations, laboratory-constructed CO_2 lasers were used to inject heat into specimens containing programmed flaws. During FY70, a laser was used having an output of 30 watts that was 100 per cent modulated at 120 hertz.[4] Since this modulation caused detectable variations in the heat flux incident on the surface of the specimen a continuous wave (CW) CO_2 laser with a constant 35 watt output was constructed in the laboratory for the FY71 effort.[5] In conjunction with the laser heat source, an infrared radiometer was used in active IRNDT investigations to detect surface temperature irregularities resulting from flaws.

For passive IRNDT investigations, a miniaturized infrared radiometer was constructed during FY71 and utilized to detect surface and near surface defects in metallic samples.[6]

The current effort was focused on the development of improved IRNDT techniques with the use of an infrared camera to detect thermal anomalies. In the current work, a high speed double-detector infrared camera was used to view samples while these samples were being heated by radiation from a CO_2 laser and by radiation from a standard 250-watt infrared lamp. In addition,

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the infrared camera was used to inspect the electronic circuit
board of a digital voltmeter since the operation of this device
was unreliable.

THEORY AND TECHNIQUES

All materials with a temperature above absolute zero con-
tinuously emit and absorb infrared radiation. The infrared
portion of the electromagnetic spectrum extends from 0.75 to
1000 micrometers (μm) and can be divided into four regions.
These regions are the near infrared (0.75 to 3.0 μm), the
middle infrared (3.0 to 6.0 μm), the far infrared (6.0 to 15.0
μm), and the extreme infrared (15.0 to 1000.0 μm).[6]

The intensity of the emitted infrared radiation is pro-
portional to the fourth power of the absolute temperature, in
accordance with the Stefan-Boltzmann law:

$$W = \varepsilon \sigma T^4$$

where

W is the radiant emittance in watts per unit area,

σ is the Stefan-Boltzmann constant (5.67×10^{-12}
cm^{-2} $°K^{-4}$),

T is the absolute temperature in degrees Kelvin, and

ε is the emissivity of the surface of the object.

Consequently, a small change in the temperature of an object
will result in a relatively large change in the radiant
emittance.

In the IRNDT method utilized, an external source is used to
heat the surface of an object under inspection. If no flaws are
present, the heat will flow evenly away from the heated surface
until equilibrium is reached. However, if a flaw is present,
this uniform flow of heat is interrupted and a thermal anomaly
(hot or cold spot) will develop in the proximity of the flaw
To detect these thermal anomalies, an infrared radiometer or an
infrared camera can be used. The conventional external source
of thermal energy is a heat lamp. In an investigation (FY70)
conducted in the Research Directorate, Weapons Laboratory at
Rock Island, the use of a CO_2 laser heat source was introduced;
this work was continued during FY71.[4,5] In the previous

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investigations, an infrared radiometer and line scanning
system were used to inspect a single line of the sample.
In the present investigation, a high-speed double-detector
infrared camera was used to inspect an area of the sample.
The use of the infrared camera for this application facil-
atated the detection and the location of flaws since the
data were presented in a form more readily interpretable
than that of the linear oscilloscope traces previously
obtained. The infrared camera method also yielded much
more information because of the x-y format, than the single-
line scan method.

Objects that actively emit infrared radiation such as
electrical circuits, transformers, motors, nuclear reactors,
and radiators can be inspected without the use of an external
heat source. For inspection of these objects, determination
of the characteristic thermal signature of the object or of
the component during normal operation is necessary. Then,
the thermal signature of a "suspect" or faulty system can be
used to identify the faulty components in that system by
comparison of the thermal signature obtained during normal
operation of the system. If a standard is unavailable,
faulty components can sometimes be located by comparison of
the thermal signatures of similar components in the system
that may be functioning properly This method is particularly
useful for location of problems such as faulty components in
electrical circuits, electrical shorts in transformers, and
defects in radiators.

INSTRUMENTATION AND PROCEDURE

An in-house constructed CO_2 laser and a standard 250
watt infrared lamp were used to heat the samples The laser
used was a longitudinally excited, split discharge, flowing
gas type with a continuous wave output variable to 35 watts
A complete description of this laser can be found in Reference
5 A schematic diagram and a photograph of the laboratory
constructed CO_2 laser are shown respectively in Figures 1 and
2.

A Dynarad, Inc., Model 210, infrared camera was used in
this investigation. This unit has an instantaneous field of
view of 10 x 10 degrees and a minimum detectable temperature
difference of 0.3°C at 30°C Two liquid nitrogen cooled
infrared detectors are used in the camera system, a mercury
cadmium telluride (HgCdTe) detector (which is most sensitive
to radiation in the 8 to 14 µm wavelength band) and an indium
antimonide (InSb) detector (which is most sensitive to radiation
in the 2-5.6 µm wavelength band) The two detectors can be

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VACUUM PUMP

50% REFLECTIVE MIRROR

65K OHMS

HIGH VOLTAGE POWER SUPPLY

6500 VOLTS

GAS SUPPLY

100% REFLECTIVE MIRROR

65K OHMS
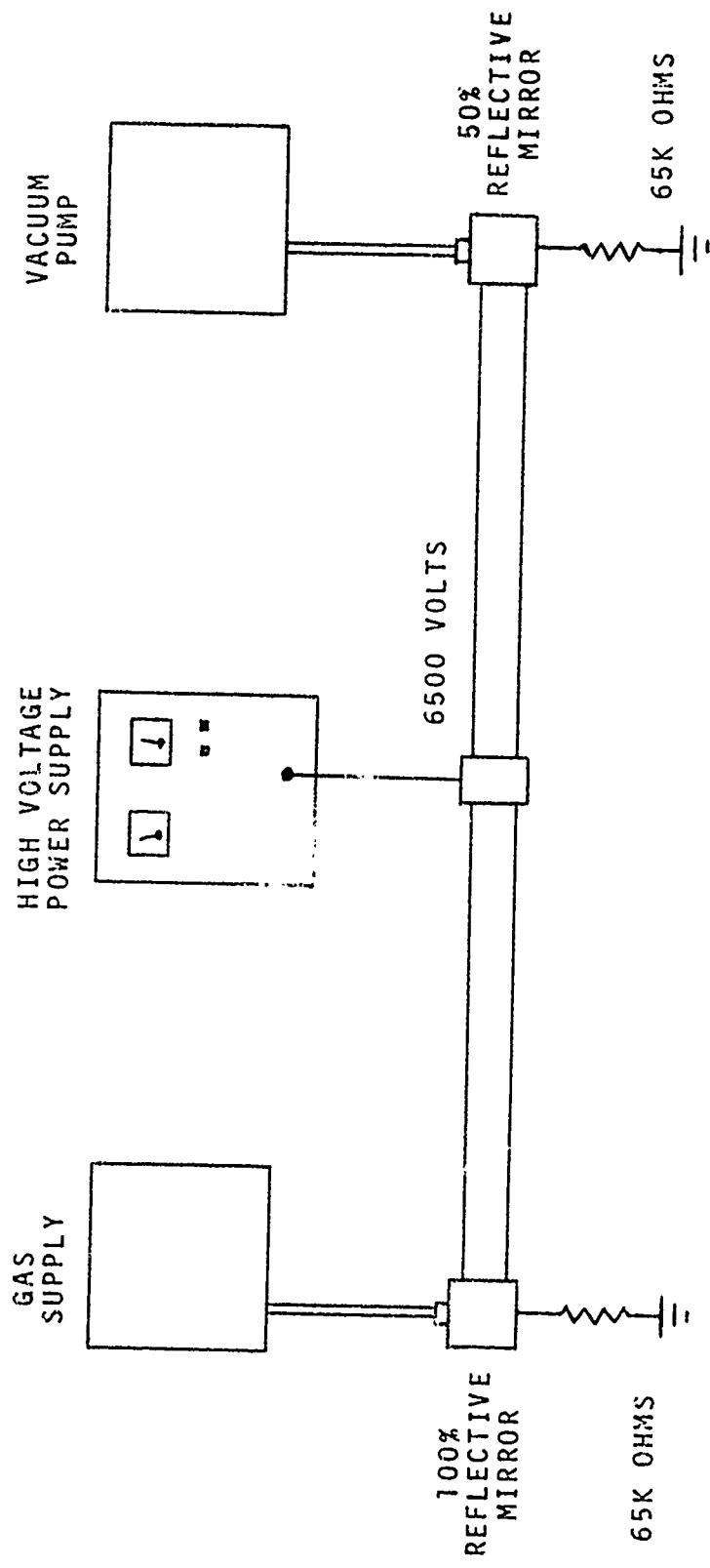
FIGURE 1   SCHEMATIC DIAGRAM OF LABORATORY-CONSTRUCTED CO_2 LASER

PROPER EYE PROTECTION MUST BE WORN AT ALL TIMES BY EVERYONE IN THIS AREA
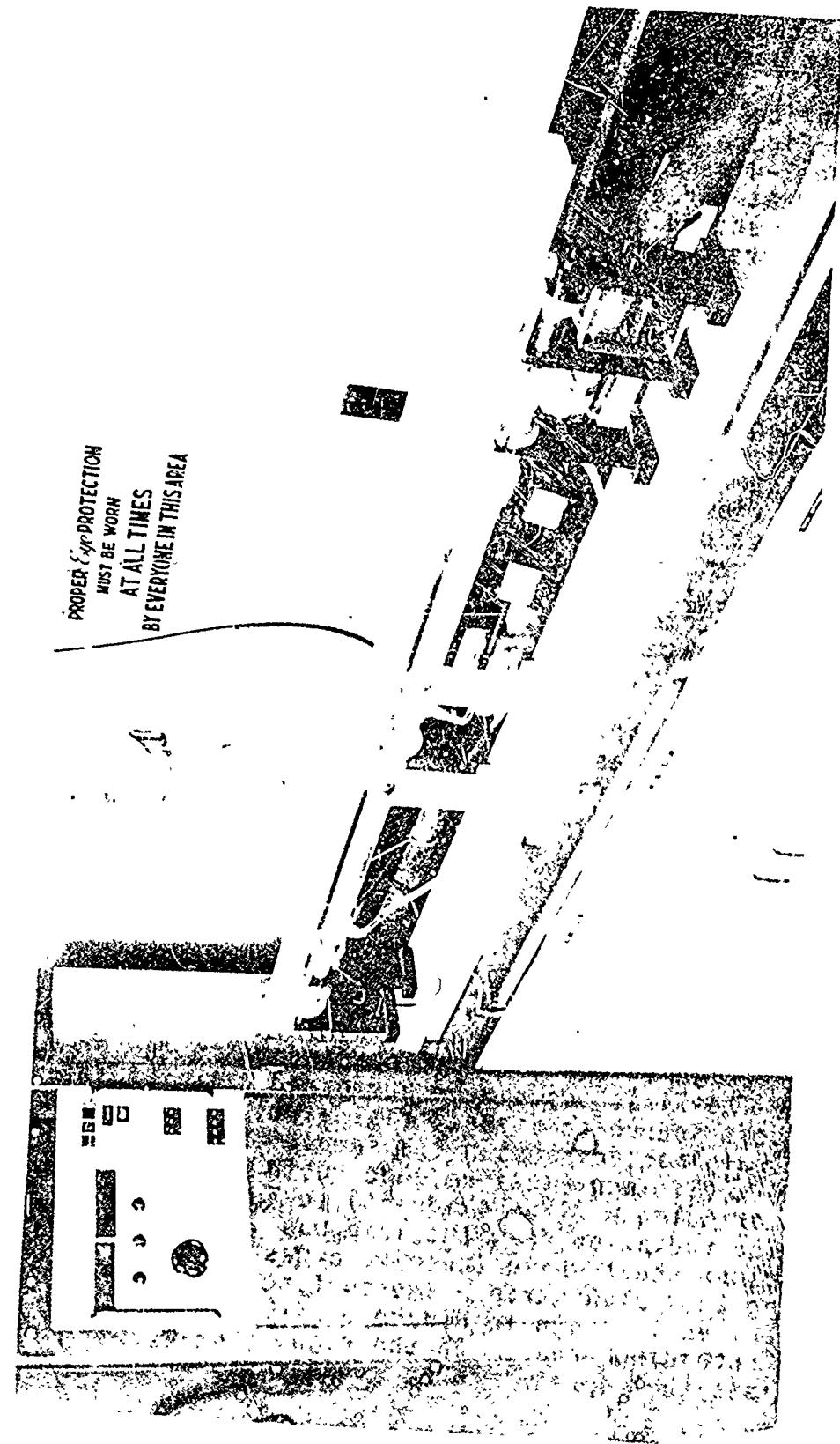
LABORATORY-CONSTRUCTED CO_2 LASER

FIGURE 2

operated individually or with their outputs added or sub-
tracted. Because of the higher sensitivity of the HgCdTe
detector, it was used solely in the tests reported

The optical unit of the camera is shown by a schematic
diagram in Figure 3. The display unit can be utilized to
display the 2-dimensional temperature-map of the object
being tested at three different frame rates: 15, 30, or
60 frames per second. Each frame contains 400, 200, or 100
lines for the respective frame rate, and each line contains
100 elements.

When the lamp was used as a heat source, the camera
was focused on the front surface of the sample while the
thermal energy was incident on the rear surface (Figure 4)
When the laser was used as a heat source, two configurations
were utilized. In the first configuration, the laser was
focused on the front surface of the sample, but was out of
the field of view of the camera (Figure 5, View a). While
this configuration was used, the heat flow across the surface
of the sample was observed. Unfortunately, the high power
radiation incident upon the surface caused the surface under
inspection to become rapidly heated; this condition, in turn,
masked any minute temperature changes that could occur because
of a subsurface flaw.

In the second configuration with the laser heat source
the infrared camera was again focused on the front of the
sample, but the laser radiation was incident on the back of
the sample (Figure 5, View b). In this configuration, four
sample heating techniques were used, a stationary focused and
unfocused beam and a scanning focused and unfocused beam

RESULTS AND DISCUSSIONS

LAMINATED STRUCTURE INSPECTION

Laminated flat samples containing programmed unbonded
areas were tested by the external heating technique previously
described. The first tests were performed with the infrared
lamp as a heat source to inspect flat aluminum/Rulon and
aluminum/Plexiglas laminates The sample used in Test 1 was
a 6 0 x 6 5 x 0.1-inch aluminum sheet with a 5 5 x 1 0 x 0 06-
inch strip of Rulon A (iron oxide-filled Teflon) bonded to the
surface The radiation from the lamp was incident on the rear
of the aluminum sheet while the camera was focused on the other
side, facing the Rulon strip The surface temperature profile
of this specimen is shown in Figure 6 with the dark (cool) spots
indicating unbonding areas On the right side of the photograph,
an area exists that appears to be a gross discontinuity This is

FOLDING
MIRROR

LINING
MIRROR

SCANNING
DRIVER

OBJECT

X-SYNC

TO
DISPLAY
UNIT

Y-SYNC

FRAMING
MIRROR

FRAMING
DRIVER

CHANNEL 2 VIDEO

CHANNEL 1 VIDEO

PREAMPLIFIER

PREAMPLIFIER

InSb

HgCdTe

2-6μm

8-14μm

DICHROIC
MIRROR

FOLDING
MIRROR
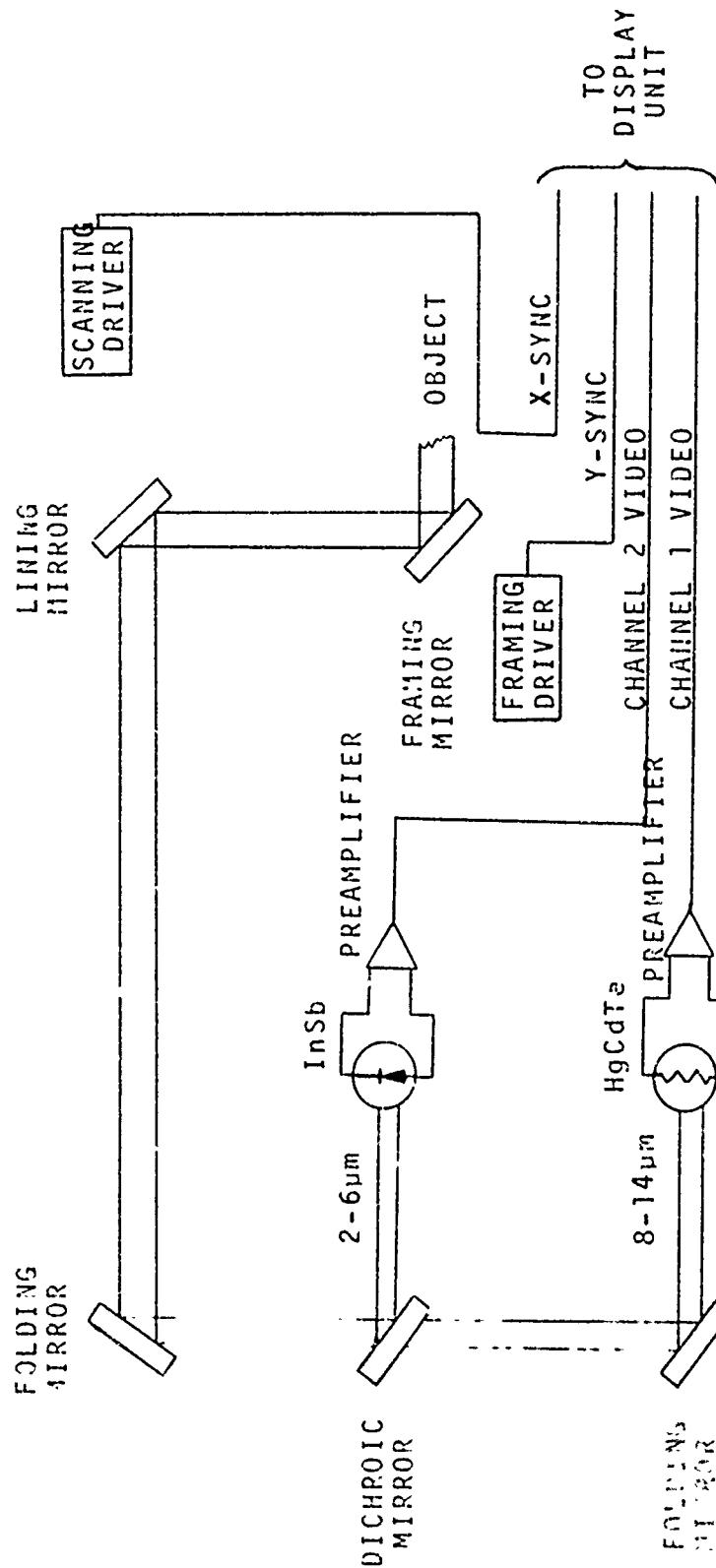
OPTICAL UNIT OF CAMERA

FIGURE 3

7

INFRARED CAMERA

DISPLAY UNIT

OPTICAL UNIT

SAMPLE
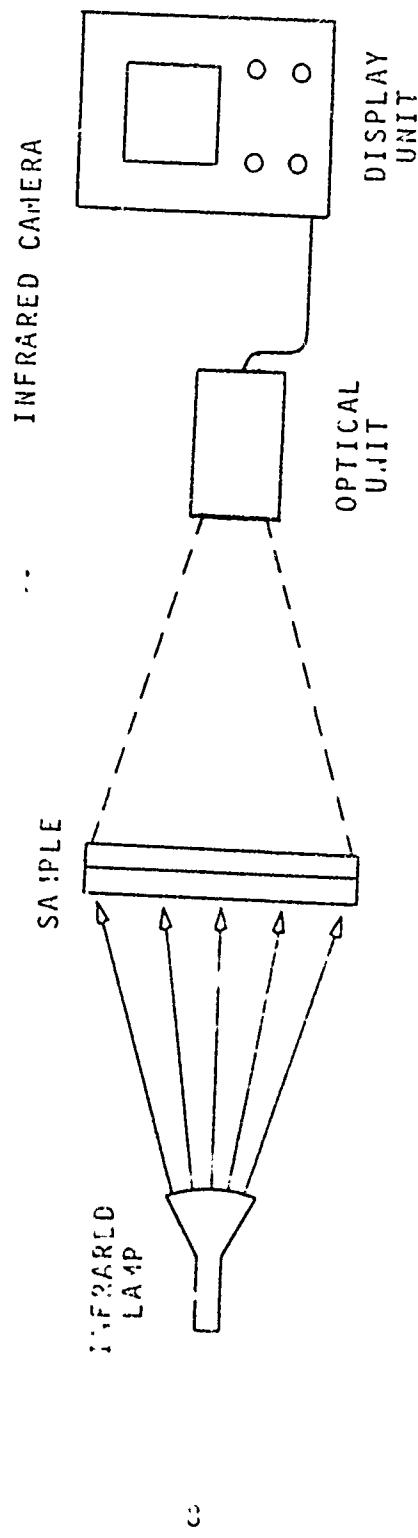
INFRARED LAMP

FIGURE 4   IRNDT TECHNIQUE WITH AN INFRARED LAMP HEAT SOURCE

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LASER   TELESCOPE   SAMPLE

INFRARED
CAMERA
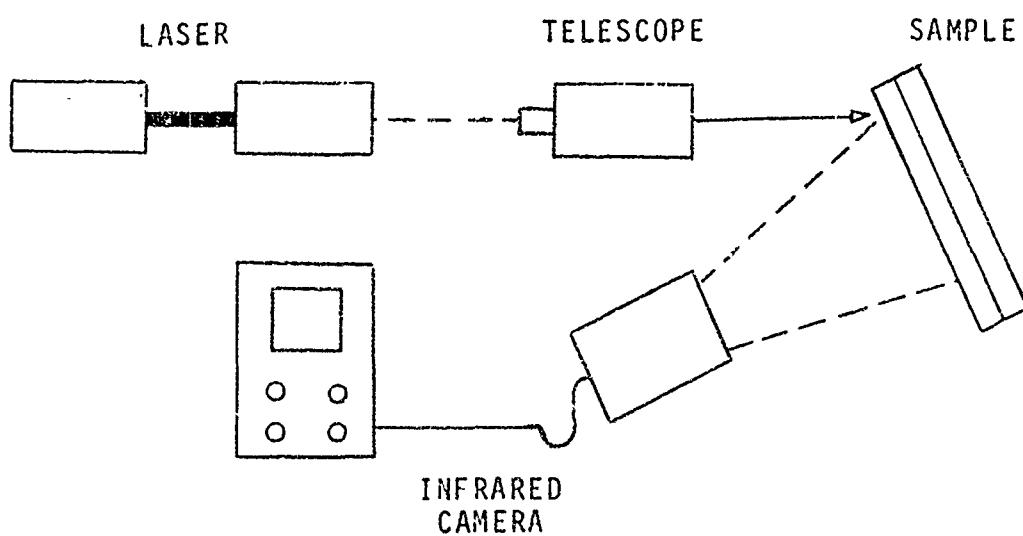
VIEW a
RADIATION INCIDENT ON THE FRONT OF THE SAMPLE

LASER   TELESCOPE   MIRROR
                                     (SCANNING
                                        OR
                                     STATIONARY)

SAMPLE

INFRARED
CAMERA
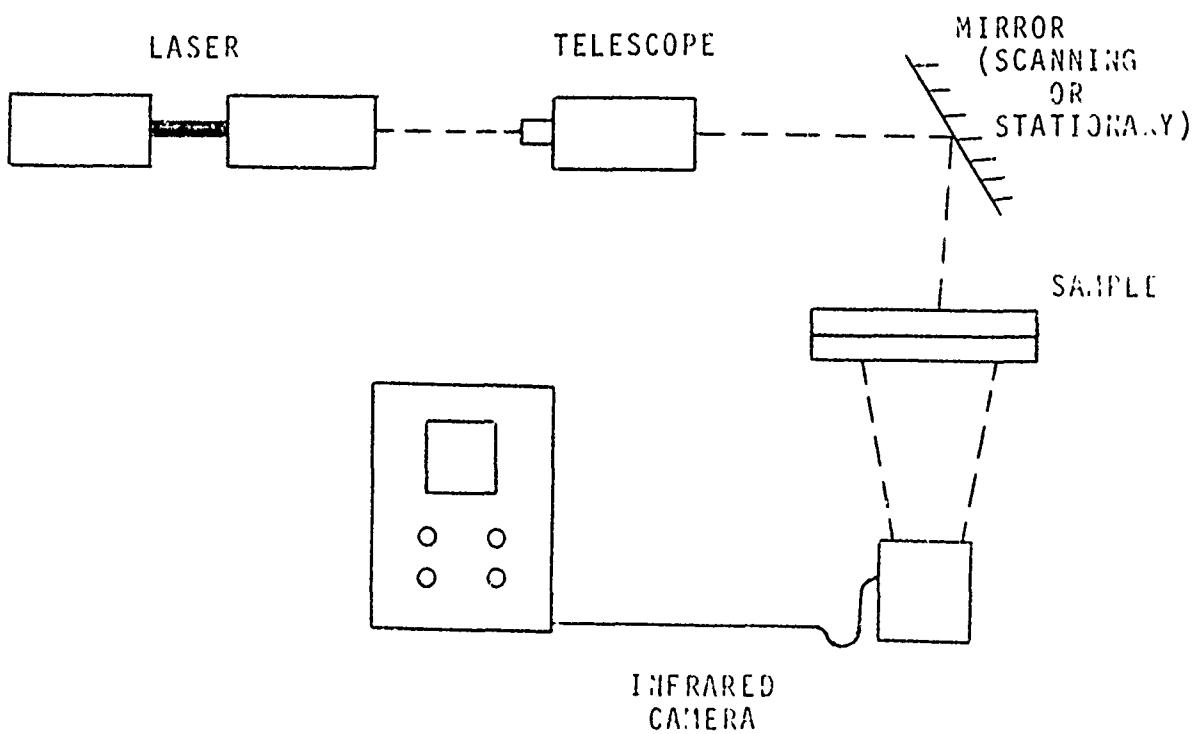
VIEW b
RADIATION INCIDENT ON THE REAR OF THE SAMPLE

FIGURE 5   IRNDT TECHNIQUE WITH A
                   LASER HEAT SOURCE

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0.18 IN² FLAW

0.1 IN² FLAW

EDGE EFFECT
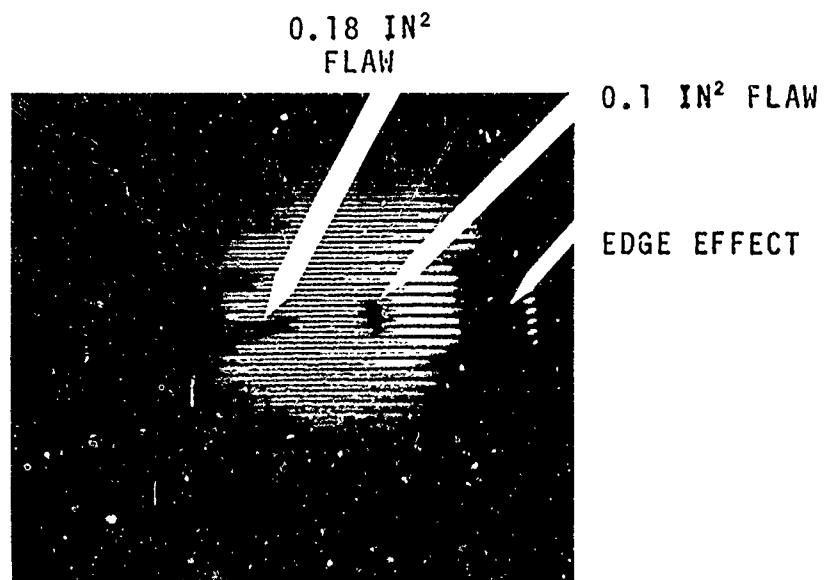
FIGURE 6 — THERMAL IMAGE OF ALUMINUM/ RULON A LAMINATE

EDGE EFFECT

1 IN² FLAW
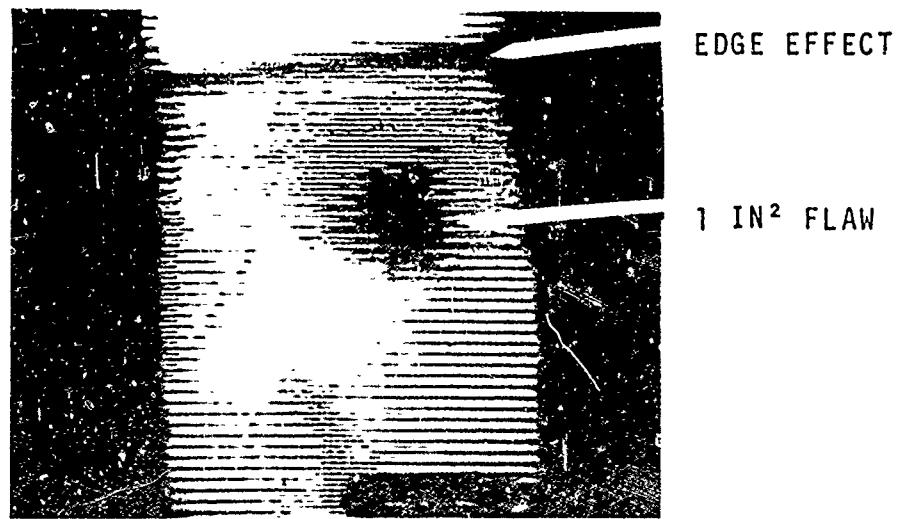
FIGURE 7 — THERMAL IMAGE OF ALUMINUM/ 0.25-INCH PLASTIC LAMINATE

caused because the Rulon strip does not extend to the edge of the aluminum sheet. Since the surface of the aluminum sheet is hotter than the surface of the Rulon, a discontinuity appears along the edge.

The sample used in Test 2 was a 5.75 x 4.375 x 0.03125-inch aluminum sheet with a 5.0 x 4.0 x 0.25-inch plastic sheet bonded to the surface. The camera was focused on the plastic sheet with the heat incident on the rear of the aluminum sheet. The resulting surface temperature profile is shown in Figure 7 with the dark spot indicative of an unbonded area. An edge effect is also shown in this figure.

The sample used in Test 3 was a 6 x 4 x 0.095-inch aluminum sheet with a 6 x 8 x 0.25-inch Plexiglas sheet bonded (with epoxy) to the surface. The aluminum sheet was heated by the lamp, and the camera was focused on the Plexiglas surface. The surface temperature-map is shown in Figure 8 with the four dark spots indicative of the unbonded areas.

The sample used in Test 4 was a 5.75 x 4.5 x 0.04-inch aluminum sheet with a 5 x 4 x 0.025-inch plastic sheet similarly bonded to the surface. As before, the aluminum sheet was heated and the camera was focused on the plastic surface. The surface temperature-map of this specimen with the two dark spots indicative of unbonded areas is shown in Figure 9.

The sample used in Test 5 with the infrared lamp was a 8 x 8 x 0.2-inch aluminum sheet with a 4 x 7 x 0.1-inch Plexiglas sheet bonded to the surface. The same heating and viewing configuration used previously was used in this case, the resulting thermal image is shown in Figure 10. The entire test specimen is not shown in the figure; actual dimensions of the section shown in the image are 5 x 3 inches.

The results shown indicate that IRNDT techniques can be reliably utilized to detect voids in the bonding mater al of laminated structures. Voids can be detected when the size of the void is small compared with the depth of the void below the surface. In addition to the detection of unbonded areas in laminated materials, the goal of this Laboratory was to determine whether the use of a CO_2 laser heat source would be feasible and whether it would improve the IRNDT technique when an area is being inspected.

In Test 1 with the laser heat source, the same aluminum/Plexiglas laminate that was inspected in the previously mentioned Test 5 with the heat lamp was reinspected

0.5 IN² FLAW   0.19 IN² FLAW

0.05 IN² FLAW
0.11 IN² FLAW
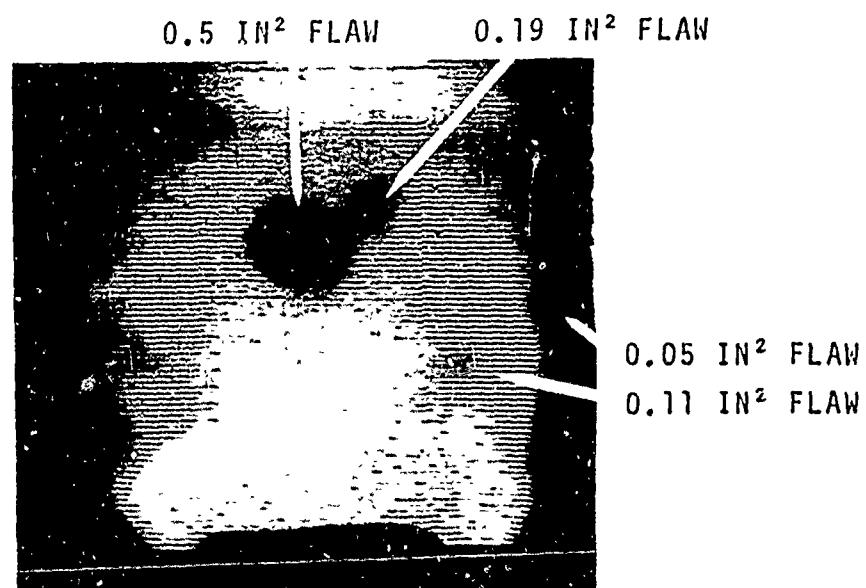
FIGURE 8   THERMAL IMAGE OF ALUMINUM/
0.25-INCH PLEXIGLAS LAMINATE

1.6 IN²
FLAW

0.13 IN² FLAW
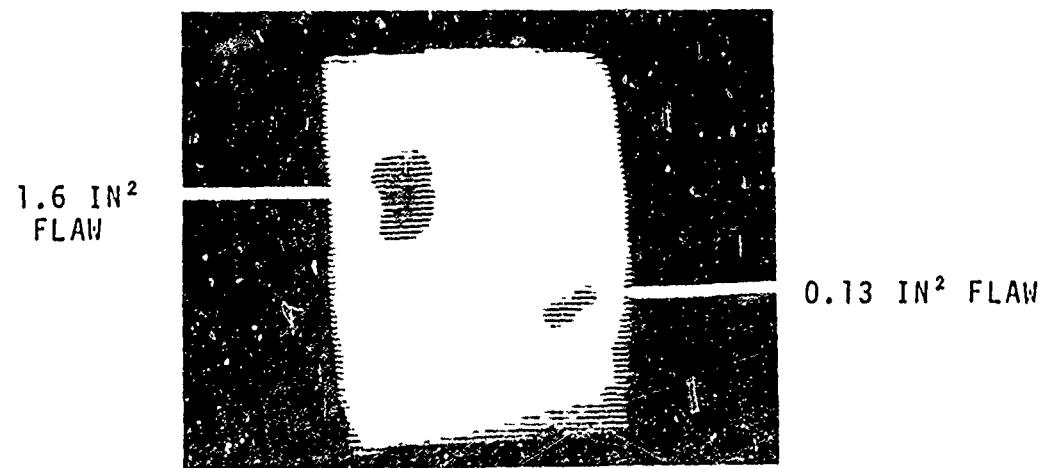
FIGURE 9   THERMAL IMAGE OF ALUMINUM/
0.025-INCH PLASTIC LAMINATE

0.2 IN² FLAW

1.25 IN² FLAW
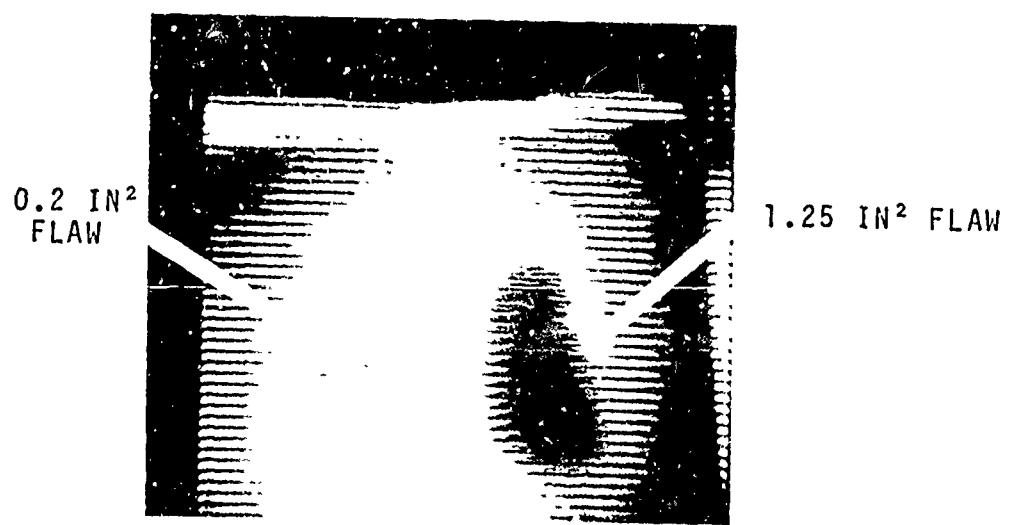
FIGURE 10   THERMAL IMAGE OF ALUMINUM/
0.1-INCH PLEXIGLAS LAMINATE

In this test, the defocused laser beam was incident on the aluminum sheet while the camera was focused on the Plexiglas surface. Two tests were performed, one with a stationary laser spot and the other with a scanning laser spot. The thermal signature of the sample being irradiated by the stationary laser spot is shown in Figure 11a. (Note the hot center and cool edges.) A situation in which this sample is being heated by the scanning spot is shown in Figure 11b. (Note the more uniform temperature distribution.) In Views a and b of Figure 11, the larger flaw is distinguishable, but the smaller flaw shown in Figure 10 is indistinguishable.

In the next test with the laser heat source, the aluminum/ Rulon A composite, previously described, was inspected. As before, the laser energy was incident on the aluminum while the camera was utilized to monitor the thermal signature of this sample. The signature that resulted from the use of a stationary unfocused laser heat source is shown in Figure 12, View a, and the signature of the sample resulting from the use of a scanning laser heat source is shown in Figure 12, View b.

The last sample tested with the laser as a heat source was the aluminum/plastic sheet laminate described previously in Test 2. The laser was again used to heat the aluminum sheet while the thermal profile of the plastic surface was monitored with the infrared camera. The thermal profile that resulted from this sample while the stationary laser was used as a heat source is shown in Figure 13, View a. The thermal signature that resulted when the sample was heated by a scanning laser spot, is shown for comparison in Figure 13, View b.

The results from the tests with the laser as the source of specimen heating clearly indicated that flaws are detectable. However, when these results were compared with those obtained with a heat lamp as a heat source, the use of a relatively low power CO_2 laser did not increase flaw detection capabilities. This is explained by the fact that none of the advantageous properties of the laser (high power density, coherence, and fine focus) were being utilized since the radiation was unfocused and the power density on the surface was low Therefore, the laser was being utilized essentially to simulate a heat lamp. When a focused beam was utilized to achieve high power densities, the resulting hot spot saturated the thermal image and masked the thermal effects due to flaws Since in this investigation, a laser was used with an output of only 35 watts when the beam is unfocused, the power density on the sample was low (0.66 watts per square centimeter) With the use of the unfocused beam from a higher power CO_2 laser having an output on the order of hundreds of watts, flaws located further below the surface and flaws in massive components would probably be detected

FLAW

VIEW a
UTILIZATION OF A STATIONARY LASER BEAM

FLAW
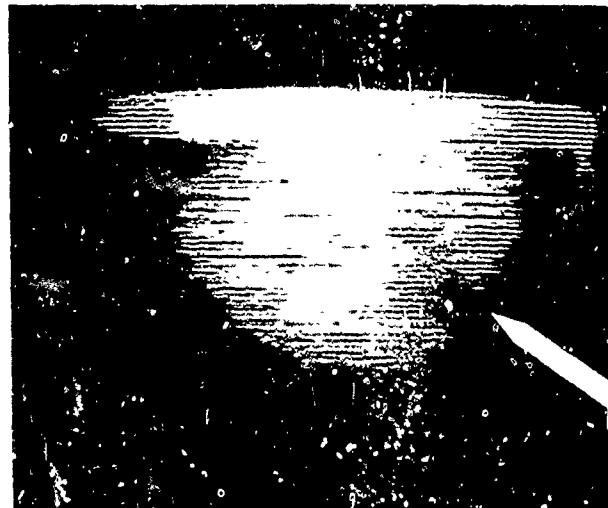
VIEW b
UTILIZATION OF A SCANNING LASER BEAM

FIGURE 11   THERMAL IMAGE OF ALUMINUM/
0.1-INCH PLEXIGLAS LAMINATE

16

FLAW

FLAW

VIEW a
UTILIZATION OF A STATIONARY LASER BEAM

FLAW

FLAW
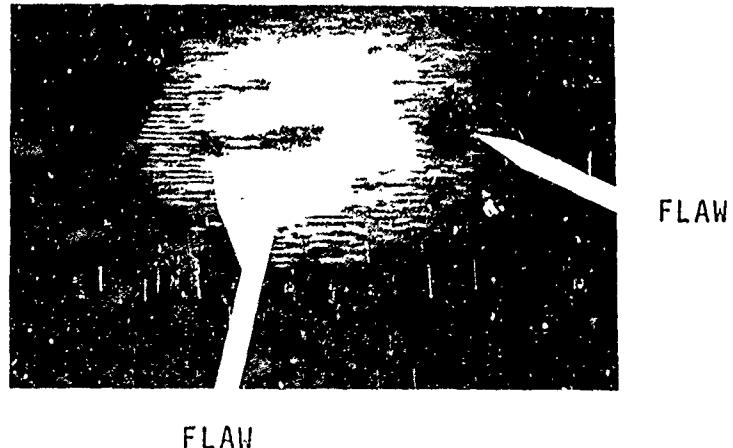
VIEW b
UTILIZATION OF A SCANNING LASER SPOT

FIGURE 12   THERMAL IMAGE OF ALUMINUM/
                   RULON A LAMINATE

FLAW   FLAW

VIEW a
UTILIZATION OF A STATIONARY LASER SPOT

FLAW   FLAW
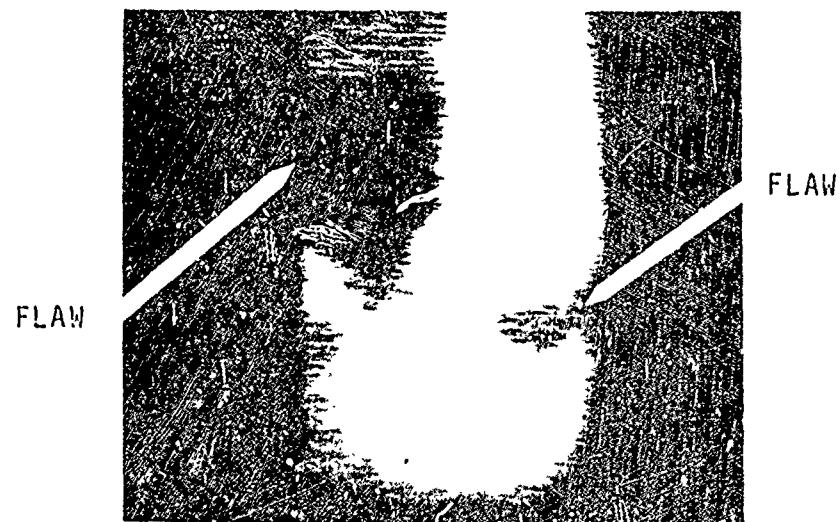
VIEW b
UTILIZATION OF A SCANNING LASER SPOT

FIGURE 13   THERMAL PROFILE OF ALUMINUM/
   0.025-INCH PLASTIC LAMINATE

When the results of the FY71 and FY72 investigations
are compared, the IRNDT technique which is best, must be
determined by physical geometry, material, and mass of the
object being tested. A laser heat source and a single-line
scanning radiometer are preferred when the surface of
interest is narrow and massive. A combination of a heat
lamp and an infrared camera is best for testing components
with relatively large areas and consisting of materials that
are adversely affected by high temperatures. The cost of the
instrumentation must also be taken into account. The cost of
an infrared radiometer plus a CO_2 laser system would be
approximately $15,000 whereas the price of an infrared camera
ranges from $17,000 to over $50,000, but the cost of a heat
lamp is negligible. Therefore, before an attempt is made to
choose the IRNDT technique best for a particular application,
the type of component being examined and the type of flaw
expected must be studied carefully.

The intelligibility of the data presented should also be
considered. Since the thermal image resembles a normal
reflected-light, representation of the object, thermal images
are much more readily interpreted than single line outputs.
In addition, the location of the flaw is easily determined
with a thermal imaging-system. However, with a scanning
radiometer system, the location of a flaw is difficult to
determine

ELECTRICAL CIRCUIT INSPECTION

During the FY72 IRNDT investigation, the electrical
circuit testing was limited to the inspection of the circuit
board of a digital voltmeter This particular instrument was
not operating reliably and had a mean time before failure of
approximately 8 hours, with the same two transistors failing
in each case.

To determine whether any abnormal thermal concentrations
were present on the circuit board, the electronics were removed
from the case and the unit was allowed to operate while the
infrared camera was focused on the circuit board A conventional
photograph of the underside of the circuit board is shown in
Figure 14, View a. The thermal image of the circuit board is
shown in Figure 14, View b The hot spot (white) in the upper
left of this view was caused by a resistor by which the board
was heated. The transistors that were of interest are located
below the hot resistor in the locations indicated An isometric
image of the circuit board is shown in Figure 14, View c In
this type of image, amplitude modulation of the horizontal line

18

VIEW a
PHOTOGRAPH

RESISTOR

VIEW b
THERMAL IMAGE

TRANSISTORS

RESISTOR

VIEW c
ISOMETRIC IMAGE

FIGURE 14   UNDER SIDE OF CIRCUIT BOARD
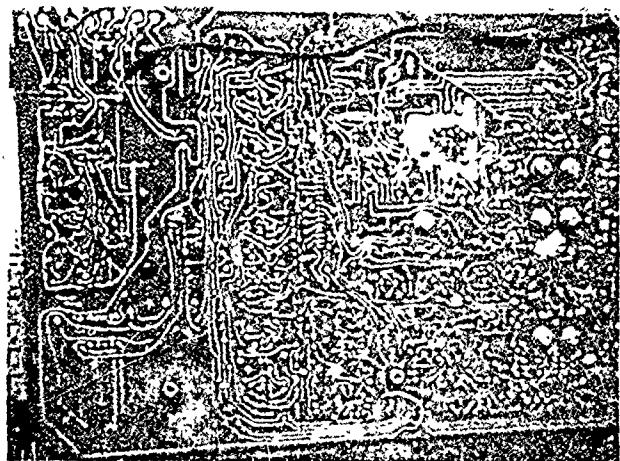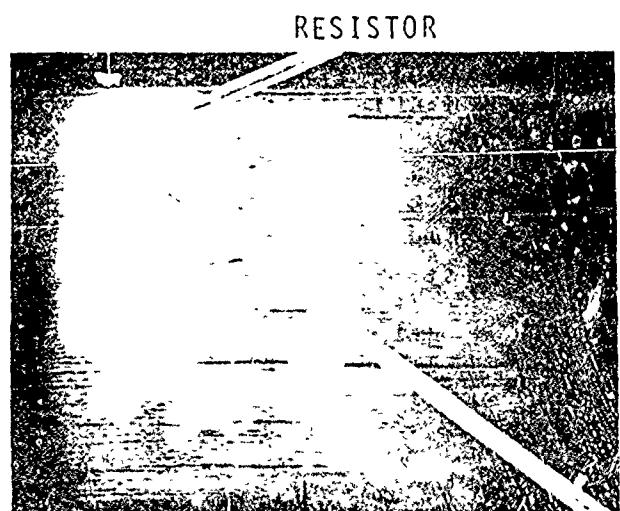
scan is used to present a 3-dimensional temperature-map. The peaks in this view indicate hot spots.

Since the thermal image of the bottom of the printed circuit board did not yield all the necessary information, the board was rotated 180° (top to bottom) and the temperature profiles of this surface were monitored. A photograph of the area under inspection is shown in Figure 15, View a. (Note. What was shown at the top in Figure 20 is now at the bottom). The thermal and the isometric images of this side of the board are shown respectively in Figure 15, Views b and c with the location of the components of interest marked. Since the transistors that had been failing after prolonged use (8 hours) were operating at a higher temperature than the comparable units in the circuit, these transistors were replaced by transistors with comparable electrical characteristics but with a higher power dissipation capability. In addition, the gold cases of these transistors, which have a very low emissivity (typically less than 0.1), were painted with ultra flat black-enamel, which has an emissivity of greater than 0.95, to improve the radiative heat transfer characteristics. After these transistors had been changed, the instrument was operated continuously for three 8-hour periods without malfunctions; the unit has also operated reliably during normal use after the test period. Therefore, the ability to use infrared nondestructive testing techniques for electrical circuit analysis was also shown during this investigation

CONCLUSIONS

The capability of the IRNDT techniques for the detection of unbonded areas in laminated structures was shown In addition, the capability of the IRNDT techniques for the detection of faulty electrcal components and for the detection of incipient failures in _lectrical circuits was demonstrated.

From the results of this IRNDT investigation, it can be concluded that the flaw detection capabilities when an infrared lamp or a low-power CO_2 laser heat source is used in conjunction with a thermal imaging device are approximately equal Since the capabilities are equal, the logical choice of a heat source for most applications, would be the infrared lamp because of the low cost and ease of operation

In addition, the use of a thermal imaging device for the inspection of electrical circuits is clearly superior to the use of a scanning radiometer because of the more intelligible format of the information presented
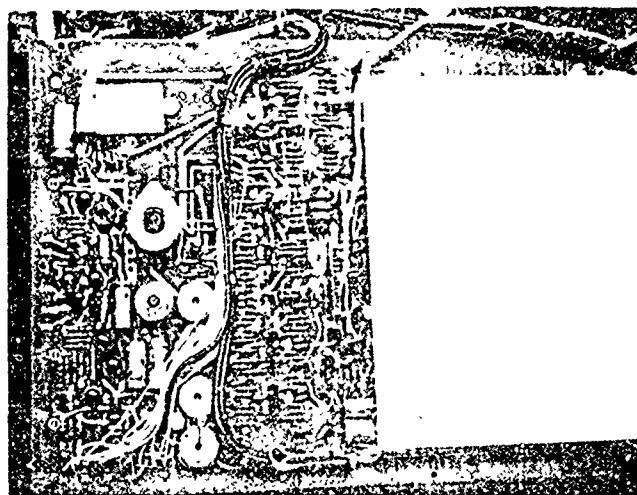
VIEW a
PHOTOGRAPH
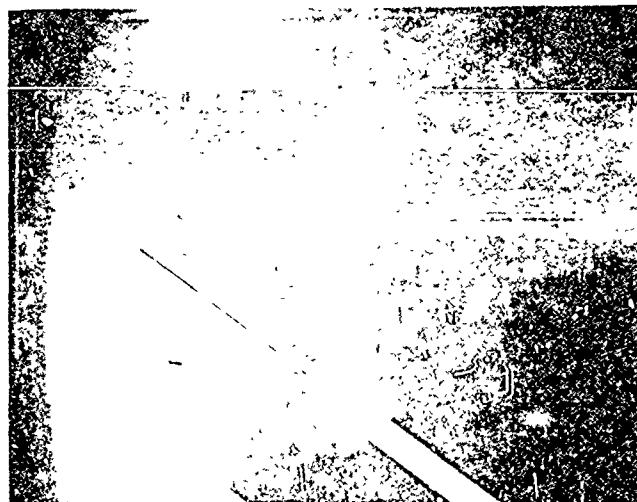
VIEW b
THERMAL IMAGE

PESISTOR   TRANSISTORS

VIEW c
ISOMETRIC IMAGE

FIGURE 15   [...] OF CIRCUIT BOARD

RECOMMENDATIONS

Further research should be directed toward the use of the techniques developed in the Research Directorate of the Weapons Laboratory at Rock Island for the inspection of particular weapon components. In addition, experiments should be performed on a series of identical samples without flaws to determine the characteristic thermal signature of the set of samples. Once the characteristic signature is determined, samples containing programmed flaws should be tested to determine the changes in the characteristic signature resulting from the flaws. This signature information should be employed to determine the feasibility of using pattern recognition techniques for the automatic inspection of components.

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